**θ -term and strong CP problem**

\[ \mathcal{L}_{\text{QCD}} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{q}(iD - M) q + \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \ldots \]

**θ-term is CP-violating**

Physical effects depend on the combination

\[ \tilde{\theta} = \theta + \text{Arg Det } M \]

\[ d_n \sim \frac{e}{m_n} \frac{m_u m_d}{m_u + m_d} \frac{1}{\tilde{\theta}} \]

\[ d_n < 0.63 \times 10^{-25} \text{ e cm} \quad \Rightarrow \quad \tilde{\theta} < 10^{-9} \]

**The CP problem:**

why \( \tilde{\theta} \) so small?

\[ \theta_{\text{QCD}} \text{ Arg Det } M \text{ unrelated} \]

makes the problem worse!
Chiral symmetry $U(1)_{PQ}$ allows to rotate $\bar{\theta}$ away.

Spontaneous breaking of anomalous global symmetry

Pseudo Goldstone Boson (PGB)

(QCD)- Axion model has large breaking scale $f_a$

Interactions are weak

Mass is small

Experiments looking for axions use coupling to two photons

$e^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} a$

Invisible axion
Consider $\phi$ light PS or S coupled to $\gamma \gamma$

$$\mathcal{L}_{\phi \gamma \gamma} = \frac{1}{8} g_{\phi \gamma \gamma} \phi \epsilon^{\mu \nu \alpha \beta} F_{\mu \nu} F_{\alpha \beta} = \phi \vec{E} \vec{B}$$

two (independent) properties:

- Mass $m$
- Coupling $g_{\phi \gamma \gamma} \equiv \frac{1}{M}$

(Current) axion experiments sensitive to $\gamma \gamma$ coupling

Other GB or PGB

- Family, Lepton num. sym. $\Rightarrow$ familons, majorons
- MetaSM theories $\Rightarrow$ $0^-, 0^+$

Even for the axion, there might be extra contributions to mass, altering relation $m_a \sim f_a^{-1}$

Interesting implications, cf. SN dimming, ...
Axions
and their relatives

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Javier Redondo
Francesc Rota
Gabriel Zsebkinszki

and: Tony Grifols
Ramon Toldrà

and: Andreas Ringwald
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OUTLINE OF THE TALK

- Strong CP, PQ, axions, light bosons with $\phi\gamma\gamma$
- $\phi\gamma\gamma$ coupling: consequences / constraints
- Recent results: CAST & PVLAS; the conflict
- Ideas to evade astrophysical constraints
- Light bosons as Dark Matter
- Planck-induced symmetry breaking and PGB DM
- Bounds on forces mediated by light bosons
Consequences of $\phi\gamma\gamma$

- Primakov-like processes allows $\gamma \rightarrow \phi$ and $\phi \rightarrow \gamma$
  (cf. Primakov process for $\pi^0\gamma\gamma$)

- $\phi\gamma$ mixing in external B-field

\[
\mathcal{L}_{\text{int}} = \mathcal{L}_{\phi\gamma\gamma} \quad \rightarrow \quad g_{\phi\gamma\gamma} \phi \vec{\epsilon} \cdot \vec{B}
\]

strength of interaction

photon polarization

\[\theta \approx \frac{B T}{M}\]
Consequences of $\phi\gamma\gamma$

Interaction states $\neq$ Propagation states

\[
|\phi'\rangle = \cos \theta |\phi\rangle - \sin \theta |\gamma\rangle \\
|\gamma'\rangle = \sin \theta |\phi\rangle + \cos \theta |\gamma\rangle
\]

transition probability

after traveling a distance $L$

\[
P(\gamma \rightarrow \phi) = \frac{1}{4} g_{a\gamma}^2 B_T^2 L^2
\]

Coherent effect

Condition *

\[
|k_\gamma - k_\phi| L \ll 2\pi \quad \Rightarrow \quad \frac{Lm_\phi^2}{E} < 1 \\
E = \text{energy (in vacuum)}
\]

* (Valid when $g_{\phi\gamma\gamma} B \ll L$ and $m_\phi^2/2E \ll E$)
Constraints on $\phi \gamma \gamma$

1. Particle physics
   \[ P (\phi \rightarrow \gamma) = \frac{1}{4} g^2 \phi \gamma \gamma B^2 L^2 \]
   \[ L m_{\text{m}}^2 E < 1 \]
   \[ M = g^{-1} \phi \gamma \gamma > 10^5 \text{ GeV} \]

2. Astrophysical
   They push (very much) terrestrial limits

3. Cosmological

EM, Toldrà
Klebart, Rabadan
Astrophysical (Energy Loss Arguments)

Production: Primakov in the stellar plasma

\[ \gamma \rightarrow \phi, Z,e \]

Emission: Weakly interacting particles leave the star

\[ \text{star} \rightarrow \phi \]

New energy loss channel accelerates star evolution

Time-scale observation constrains exotic energy drain from the star:

\[ M > 2 \times 10^{10} \text{ GeV} \ (m < 10 \text{ keV}) \]

Also SN87 A \[ M > 10^9 \text{ GeV} \ (m < 50 \text{ MeV}) \]

Raffelt

Horizontal Branch Stars
Gamma-rays from SN

Part of the $\phi$-flux produced in the SN core can be (partially) converted back to photons in galactic B

Limits on $\gamma$-flux by GRS at the time of observation of $\nu$-flux in 02.1987

In future galactic SN, we might get a signal since we have now more sensitive gamma-rays detectors in satellites
Recent experimental results (small masses)

CAST (CERN)  

PVLAS (INFN)
Sitges Cine Festival (Horror and Fantastic)

Get inspiration for next experiments!
CAST search

Idea: Sun is source of axion-like particles. Use B to convert them back to photons (of few keV, X-rays)

NO signal (at the moment)

$M > 0.9 \times 10^{10}$ GeV
($m < 0.02$ eV)

K. Zioutas et al. PRL 94 (2005)

Comments: Past helioscopes; Crystal search (Bragg-Primakov)
PVLAS search

**ROTATION of polarization plane of laser in B field**

\[ \alpha = (3.9 \pm 0.5) \times 10^{-12} \text{ rad/pass} \]

A possible interpretation:

\[ \overline{\epsilon} \cdot \overline{B} = \epsilon_\parallel B \]

Selective absorption (dichroism)

\[ \begin{align*}
B & \approx 5T, \quad L \approx 1m, \quad N \approx 4.4 \times 10^5 \\
M & = g^{-1} \phi \gamma \gamma \\
0.7 \times 10^{-9} \text{ eV} & < m < 2 \text{ meV}
\end{align*} \]
Even if particle interpretation is correct, this particle would NOT be the standard axion
PVLAS, CAST & the STARS

Obvious and dramatic conflict!

PVLAS strength of interaction leads to $\mathcal{L}_{exotic} \sim 10^6 \mathcal{L}_\odot$

Difficult problem; not easy to circumvent
Future (experimental)

CAST
- higher $m$ (gas)
- Lower photon energy

PVLAS
- higher $m$ (gas)
- Search induced ellipticity

New experiments welcome
For example post-HERA

$\phi \gamma \gamma = \frac{1}{8} g \phi \gamma \gamma \phi \epsilon_{\mu \nu \alpha \beta} F_{\mu \nu} F_{\alpha \beta}$

$\vec{E} \cdot \vec{B} = \epsilon_{\parallel} B$

$L_{\text{int}} = L_{\phi \gamma \gamma}$

$\theta \approx B T M$

$|k_{\gamma} - k_{\phi}| L \ll 2\pi$

$g \phi \gamma \gamma B \ll L$ and $m_{\phi}^2 / 2E \ll E$

Should be present if rotation signal is due to $\phi \gamma \gamma$
Letter of Intent

QED Test and Axion Search by means of Optical Techniques

To the CERN SPSC

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Abstract

The re-use of recently decommissioned 15-meter long twin aperture LHC superconducting magnet prototypes, providing a transverse magnetic field $B \approx 9.5$ T offers a unique opportunity for the construction of a new powerful two-in-one experiment to investigate the properties of the vacuum by means of optical techniques. Linearly polarised laser light beams will be used as probes inside vacuum chambers housed inside superconducting magnet apertures. One of the apertures will be dedicated to the measurements of the Vacuum Magnetic Birefringence (VMB) and optical absorption anisotropy whereas the other one will be used to detect the photon regeneration from axions using “a shining light through the wall”. The VMB predicted by the QED theory is expected to be measured for the first time and the CPT symmetry precisely tested. The values or the limiting values of mass and coupling constant to two photons of weakly interacting scalar or pseudo-scalar particles like axions are also aimed to be deduced from a sizeable deviation of the QED prediction. In case of null result for axion search and with the most conservative view concerning the detection technique, the limits of both parameters, i.e. mass and di-photon coupling constant, can be improved by at least 2 orders of magnitude with respect to present reference results obtained with a purely laboratory experiment. The interest in axion search, providing an answer to the strong-CP problem, lies beyond particle physics since such hypothetical neutral light spin zero particle is considered as one of the good dark matter candidates, and the only non-supersymmetric one.

Photon Regeneration from Pseudoscalars at X-ray Laser Facilities

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Recently, the PVLAS collaboration has reported an anomalously large rotation of the polarization of light in the presence of a magnetic field. As a possible explanation they consider the existence of a light pseudoscalar particle coupled to two photons. In this note, we propose a method of independently testing this result by using a high-energy photon regeneration experiment (the X-ray analogue of “invisible light shining through walls”) using the synchrotron X-rays from a free-electron laser (FEL). With such an experiment the region of parameter space implied by PVLAS could be probed in a matter of minutes.

* Contactperson
A way out of the puzzle is to have a model where the Sun emits much less axion-like particles than expected. There would be less energy loss and thus stellar limit are avoided. CAST limit not valid because it assumes “solar-standard” $\phi$ - flux.

I discuss two possibilities:

1) Trapping
2) Suppression of production
1) Trapping

Strongly interacting $\phi$

$\phi$ would follow a random walk on its way out of the Sun (like photons). When emitted would have much less energy than when produced in the core.

Problem: a strong interaction should have been seen elsewhere

Interact through mediators?
II) Suppression of production

Required suppression to make compatible PVLAS with stellar limits (and a fortiori with CAST)

\[
\left| F \right|^2 \frac{1}{M^2_{\text{pvlas}}} \frac{1}{M^2_{\text{pvlas}}} < \left[ \frac{1}{M^2_{\text{cast}}} \right] \frac{1}{M^2_{\text{cast}}}
\]

\[
\Rightarrow \left| F \right| < 2 \times 10^{-9}
\]

A difference between the lab & the solar plasma

\[ |q^2| \sim 0 \quad \rightarrow \quad |q^2| \sim \text{keV}^2 \]

Suppression F due to a (low scale) form-factor effect
Form factor for $0^-$ mesons

Form factor $F$ in $\pi^0 \gamma \gamma$ or $\eta \gamma \gamma$ when $\gamma$ virtual?

THEORETICAL EXPECTATIONS

effective interaction

$$\mathcal{L} = \frac{1}{\Lambda} \pi \epsilon^{\mu \nu \alpha \beta} F_{\mu \nu} F_{\alpha \beta}$$

Not expected to be valid at arbitrarily high energies

$\Rightarrow$ Variation with energy

VMD model

$\Lambda \sim M_\rho$

Quark triangle

$\Lambda \sim M_{u,d}$

pQCD, chiral theories

$\Lambda \sim M_{\text{had}}$

AND ...
... IT IS OBSERVED !!

\[ |Q^2| < M_{had} \sim M_\rho \]

\[ |Q^2| >> M_{had} \sim M_\rho \]

Transition form factors
Axion-like particle may be composite

Key point: Composite particle has a form factor

Postulate that

\[ \phi \text{ IS A COMPOSITE PARTICLE} \]

NEED

- New constituents
- New confining forces

there will be form-factor effects with a new low-energy scale

Difference between being composite or being elementary
Evaluate new scale

Assume only one constituent \( f \) (fermion, SM singlet) & SU(N) for new forces (nothing to do with color)

To evaluate new scale:

- calculate triangle diagram with internal fermion for off-shell photons

\[
|F| < 2 \times 10^{-9} \quad \Rightarrow \quad \Lambda \sim M_f < 2 \times 10^{-2} \text{eV}
\]

MAIN RESULT:

new scale

Notice: same order than mass \( m \) of \( \phi \)

(Not necessary a priori, perhaps a clue)
\[ f_{\gamma\gamma} = -\frac{gM}{\pi^2m_{\pi}^2}\arcsin^2(m_{\pi}/2M) \]

\[ \lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz \]

\[
F(s_1, s_2; s_0) = \frac{gM}{2\pi^2f_{\gamma\gamma} \lambda^1}(s_0, s_1, s_2) \times \\
\sum_{i=0,1,2} \left[ Li_2 \left( \frac{Y_i}{Y_i - Y_{+i}} \right) + Li_2 \left( \frac{Y_i}{Y_i - Y_{-i}} \right) - Li_2 \left( \frac{Y_i - 1}{Y_i - Y_{+i}} \right) - Li_2 \left( \frac{Y_i - 1}{Y_i - Y_{-i}} \right) \right]
\]

\[ Li_2(x) = -\int_0^x \frac{\ln(1-t)}{t} dt \]

\[ Y_i = \frac{1}{2} \left[ 1 + \frac{s_j + s_k - s_i}{\lambda^1(s_0, s_1, s_2)} \right], \quad i \neq j \neq k ; \quad i \neq k \]

\[ Y_{\pm i} = \frac{1}{2} \left[ 1 \pm \sqrt{1 - \frac{4M^2 - i\varepsilon}{s_i}} \right] \]

\[ s_1 > s_2 >> s_0 = m_{\pi}^2 \quad F(s_1, s_2; s_0) \rightarrow \frac{1}{2|s_1 - s_2|}{\ln^2|\frac{s_1 - s_2}{s_0^2}|} \]
To QCD or not to QCD

We have been inspired by QCD, $\pi'$s & $q$
But we don't know if QCD is the reference model
until last consequences (like it was in Technicolor)

Need low energy scale $\ll$ keV, in any case

For example $F \sim (\Lambda^2/Q^2)^n$  $\Lambda$ a few eV for $n=2$

If similar to QCD... $\eta$ vs. $\eta'$

$q_f \neq 0$ but very small

not to have undesirable consequences

(paraphoton models give arbitrarily epsilon-charges)

Future: Model building and look for signatures
OUTLINE OF THE TALK

- Light bosons as Dark Matter
- Planck-induced symmetry breaking and PGB DM
- Bounds on forces mediated by light bosons
Relic density of particles coupled to photons

Work out $\phi$ decoupling in the early universe

Processes

$e^-\phi \leftrightarrow e^-\gamma$

$\gamma\phi \leftrightarrow e^-e^+$

(and any other charged particle in equilibrium)

Freeze-out

$H(T_f) = \Gamma(T_f)$

Interaction rate

Entropy release of annihilating species

Finally Find parameters leading to DM $\phi$
Cosmological constraints (Other than BBN)

For larger $m$, necessary to consider effects of unstable $\phi$

Injection of energy $m$ at a finite lifetime $\tau_\phi$

Depending on $\tau_\phi$ there might be cosmological effects on:
Photon Background, CMBR distortion or D-fission

DM was here

No DM

<table>
<thead>
<tr>
<th>log m</th>
<th>neV</th>
<th>μeV</th>
<th>meV</th>
<th>eV</th>
<th>keV</th>
<th>MeV</th>
<th>GeV</th>
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</thead>
<tbody>
<tr>
<td>SN1987A (γ-ray burst)</td>
<td>He burning stars</td>
<td>SN1987A (E loss)</td>
<td>BBN</td>
<td>CMBR distortion</td>
<td>D-fission</td>
<td>Photon background</td>
<td>log 1/g (GeV)</td>
</tr>
</tbody>
</table>

\[ L_m^2 E < 1 \quad M = g - 1 \phi \gamma \gamma > 2 \times 10^3 \text{GeV} \]
\[ M > 2 \times 10^{10} \text{GeV} \quad (m < 10 \text{ keV}) \]
\[ M > 10^{12} \text{GeV} \quad (m < 10^{-9} \text{ eV}) \]
\[ e^{-\phi} \leftrightarrow e^{-\gamma} \gamma \phi \leftrightarrow e^{-e^+} e^{-} \rightarrow H (T_f) = \Gamma (T_f) \]
\[ \Omega = \frac{\rho}{\rho_c \tau_\phi} \]
We have assumed thermal production due to the coupling to photons.

In realistic models:

- Other couplings
- Other production mechanisms

DM candidates

Most famous example:
QCD-axions is a DM candidate.
A model with PGB

Global symmetries

are expected to be (explicitly) broken by quantum gravity effects

\[ V = V_{\text{sym}} + V_{\text{non-sym}} \]

Consider one scalar field, U(1) symmetry

[Equation]

\[ V_{\text{sym}} = \frac{1}{4} \lambda [|\Psi|^2 - v^2]^2 \]

\[ V_{\text{non-sym}} = -g \frac{1}{M_P^{n-3}} |\Psi|^n (\Psi e^{-i\delta} + \Psi^* e^{i\delta}) \]

\( g \) could be exponentially small

Planck-mass suppressed

(most simple) not invariant piece

\( n \geq 4 \)
A model with PGB

Spontaneous breaking in presence of a small explicit breaking

\[ \Psi = \phi e^{i\theta/v}, \]

\[ m_\theta^2 = 2g \left( \frac{v}{M_P} \right)^{n-1} M_P^2 \]

(Numerical integration of eqs.)
PGB dark matter

Astrophysics + cosmology constrain the parameter space of the model

Very short lived
Not cosmo-interesting

$$m_\theta \lesssim 20 \text{ eV}$$

$$g < 10^{-30}$$
Realistic models have couplings of axion-like particles to matter

Other effects:
Violation of the equivalence principle
Interest in new (non-gravitational) forces

Experiments: were motivated by (false alarm) 5th force claim

Theory: x-dimensions, models with light scalars, etc

Axion and other PS lead to spin-dependent forces

I restrict here to forces mediated by scalar or vector coupled to lepton number
Long-range leptonic forces

\[ \alpha_L < 10^{-48} - 10^{-49} \]

from Eotvos-type experiments

\[ \left( \frac{m_p}{M_P} \right)^2 \sim 10^{-38} \]
\[ \left( \frac{m_e}{M_P} \right)^2 \sim 10^{-45} \]

Limit improved by considering the effect on solar \( \nu \) oscillations

Solution to \( \nu_\odot \)-problem: LMA resonant MSW matter oscillations

\[ \Delta m^2 = 5.5 \times 10^{-5} \text{eV}^2 \]
\[ \sin^2 2\theta = 0.83 \]
Long-range leptonic forces

New contribution

\[ \langle \nu_e | H_{\text{int}} | \nu_e \rangle = \sqrt{2} G_F N_e + V_L \]

\[ V_L(r) = \frac{\alpha_L}{r} \int_0^r d^3r N_e \]

Demand not to spoil \( \nu_\odot \) solution

\[ \alpha_L \leq 6.4 \times 10^{-54} \]

\( 10^5 \) improvement

free from screening effects
valid for ranges > solar radius
If PVLAS signal confirmed, and it is due a new particle coupled to photons, we need a model to explain why astrophysical bound are not valid.

We have presented a model where the new particle is composite and there is a low energy scale. The model allows to evade astrophysical constraints.
E. Masso and R. Toldra,
``On a light spinless particle coupled to photons,"

J.A. Grifols, E. Masso and R. Toldra,
``Gamma rays from SN1987A due to pseudoscalar conversion,"

E. Masso and R. Toldra,
``New constraints on a light spinless particle coupled to photons,"